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Mitigating ammonia and PM generation of cage-free henhouse litter with solid additive and liquid spray

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Abstract

A number of chain restaurants, retailers, and grocers in the U.S. have pledged to source only cage-free (CF) eggs in the foreseeable future (e.g., by 2025) due to marketing reasons or concerns over animal welfare. However, CF housing has some inherent challenges, and a predominant one is poor air quality, i.e., ammonia gas (NH3) and particulate matter (PM), and increased emissions. Spraying a liquid agent such as electrolyzed water (EW) can effectively suppress PM generation of CF henhouse litter. However, liquid spray can enhance NH3 generation because it increases the litter moisture content (LMC). Application of acidic liquid to the litter would help control NH3 while suppressing PM, but con-cerns arise about the potential corrosive effect of acidic liquid on housing equipment. To overcome this dilemma, this study evaluated the effect of applying PLT, a commercial poultry litter additive (LA), on NH3 emissions of CF hen litter while spraying it with neutral EW (NEW) at a rate of 25 mL kg-1 dry litter d-1. The PLT application rates were 0.3, 0.6, and 0.9 kg m-2, denoted as Low-LA, Med-LA, and High-LA, respectively. CF litter was placed inside dynamic emission chambers and automatically stirred to mimic hen scratching. PLT was topically applied onto the litter on day 1; NEW was sprayed daily for 11 d, followed by a 3 d non-spray period (i.e., 14 d per trial); and each regimen was replicated four times. The ammonia emission rate (ER) of the control (no LA), Low-LA, Med-LA, and High-LA regimens (mean ±SE) was, respectively, 0.76 ±0.05, 0.55 ±0.06, 0.37 ±0.04, and 0.16 ±0.02 g kg-1 dry litter d-1, i.e., 28% to 79% reduction by the treatments. The NH3 reduction efficiency was linearly proportional to the PLT application rate, with higher application rate resulting in lower litter pH ($p < 0.05$). At the end of each trial (d14), the Med-LA and High-LA regimens still showed relatively low NH3 emissions, suggesting the need for a longer measurement period in future studies. The NEW spray increased LMC by up to 60% after 11 once-a-day sprays, which reduced PM2.5, PM10, and TSP levels from 3.83, 6.39, and 7 mg m-3 to 0.07, 0.14, and 0.15 mg m-3, respectively. After a 3 d spray suspension, the PM levels rebounded to 0.72, 1.02, and 1.12 mg m-3 for PM2.5, PM10, and TSP, respectively, due to decreased LMC. Field verification of the mitigation efficacy and an economic assessment of the method are warranted.

Keywords

Air quality, Alternative hen housing, Animal and worker health, Litter treatment

Disciplines

Agriculture | Bioresource and Agricultural Engineering | Poultry or Avian Science

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MITIGATING AMMONIA AND PM GENERATION OF CAGE-FREE HENHOUSE LITTER WITH SOLID ADDITIVE AND LIQUID SPRAY

L. Chai, H. Xin, Y. Zhao, T. Wang, M. Soupir, K. Liu

ABSTRACT. *A number of chain restaurants, retailers, and grocers in the U.S. have pledged to source only cage-free (CF) eggs in the foreseeable future (e.g., by 2025) due to marketing reasons or concerns over animal welfare. However, CF housing has some inherent challenges, and a predominant one is poor air quality, i.e., ammonia gas (NH_3) and particulate matter (PM), and increased emissions. Spraying a liquid agent such as electrolyzed water (EW) can effectively suppress PM generation of CF henhouse litter. However, liquid spray can enhance NH_3 generation because it increases the litter moisture content (LMC). Application of acidic liquid to the litter would help control NH_3 while suppressing PM, but concerns arise about the potential corrosive effect of acidic liquid on housing equipment. To overcome this dilemma, this study evaluated the effect of applying PLT, a commercial poultry litter additive (LA), on NH_3 emissions of CF hen litter while spraying it with neutral EW (NEW) at a rate of 25 mL kg^{-1} dry litter d^{-1}. The PLT application rates were 0.3, 0.6, and 0.9 kg m^{-2}, denoted as Low-LA, Med-LA, and High-LA, respectively. CF litter was placed inside dynamic emission chambers and automatically stirred to mimic hen scratching. PLT was topically applied onto the litter on day 1; NEW was sprayed daily for 11 d, followed by a 3 d non-spray period (i.e., 14 d per trial); and each regimen was replicated four times. The ammonia emission rate (ER) of the control (no LA), Low-LA, Med-LA, and High-LA regimens (mean ±SE) was, respectively, 0.76 ±0.05, 0.55 ±0.06, 0.37 ±0.04, and 0.16 ±0.02 g kg^{-1} dry litter d^{-1}, i.e., 28% to 79% reduction by the treatments. The NH_3 reduction efficiency was linearly proportional to the PLT application rate, with higher application rate resulting in lower litter pH ($p < 0.05$). At the end of each trial (d14), the Med-LA and High-LA regimens still showed relatively low NH_3 emissions, suggesting the need for a longer measurement period in future studies. The NEW spray increased LMC by up to 60% after 11 once-a-day sprays, which reduced $PM_{2.5}$, PM_{10}, and TSP levels from 3.83, 6.39, and 7 mg m^{-3} to 0.07, 0.14, and 0.15 mg m^{-3}, respectively. After a 3 d spray suspension, the PM levels rebounded to 0.72, 1.02, and 1.12 mg m^{-3} for $PM_{2.5}$, PM_{10}, and TSP, respectively, due to decreased LMC. Field verification of the mitigation efficacy and an economic assessment of the method are warranted.*

Keywords. *Air quality, Alternative hen housing, Animal and worker health, Litter treatment.*

A number of chain restaurants, retailers, and grocers in the U.S. have announced a transition to sourcing only cage-free (CF) eggs in the foreseeable future (e.g., by 2025) (Xin, 2016; UEP, 2016). According to the number of pledges to date, meeting the pledged demand by 2025 would require more than 70% of the current U.S. layer stock. While CF housing allows birds to better perform their natural behaviors (e.g., foraging, dustbathing, wing-flapping), which are limited in conventional cage housing systems, an inherent challenge with CF housing is the poor indoor air quality, such as high ammonia (NH_3), particulate matter (PM), and airborne bacteria (AB) levels, especially during cold weather (Xin et al., 2011; Adell et al., 2015; Zhao et al., 2015; Winkel et al., 2016). The recommended NH_3 threshold in pullet and layer housing is 25 ppm (18 mg m^{-3}) (UEP, 2016). According to the National Institute for Occupational Safety and Health (NIOSH), the guidelines for 8 h average and short-term (15 min) NH_3 exposure limits for workers are 25 ppm (18 mg m^{-3}) and 35 ppm (27 mg m^{-3}), respectively (NIOSH, 2016). Studies have demonstrated that NH_3 levels in CF hen houses are considerably higher than in conventional cage (CC) or enriched colony (EC) housing systems, and the levels can exceed the recommended NH_3 threshold in winter (Hayes et al., 2013; Shepherd et al., 2015; Zhao et al., 2015). The 2008 U.S. Environmental Protection Agency rule that exempted animal feeding operations from the Comprehensive Emergency Response Compensation and Liability Act (CERCLA) and the

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Emergency Planning and Community Right to Know Act (EPCRA) was recently vacated (UEP, 2017). Consequently, animal farms of any size with ammonia emissions in excess of 100 lb (45.5 kg) per day will be required to report their emissions to federal, state, and local emergency response authorities. In addition to high NH_3 levels, PM levels and emissions of CF houses have been reported to be 6 to 8 times higher than for their CC and EC counterparts (Zhao et al., 2015; Shepherd et al., 2015). Therefore, mitigating NH_3 and PM levels is imperative to protecting the well-being of the animals and caretakers, as well as improving the environmental stewardship of CF egg production.

The high NH_3 levels of CF houses primarily arise from the extended accumulation of manure on the litter floor, whereas the high PM levels primarily arise from dustbathing and foraging activities of the birds on the litter. As a result, reducing NH_3 and PM levels in CF houses is more complex than in manure-belt cage or EC houses. Spraying a liquid agent such as electrolyzed water (EW) has been shown to be conducive to suppressing PM and airborne bacteria (AB) from litter in CF settings (Zhao et al., 2014; Zheng el al., 2014; Chai et al., 2017). The reduction efficiencies for PM and AB reached 50% to 70% after spraying acidic EW at dosages of 80 to 125 mL m^{-2}. However, spraying liquid on litter can enhance NH_3 emissions because of the increased litter moisture content (LMC). Application of low pH liquid to litter would help control PM and NH_3 at the same time, but concerns arise about the potential corrosive effect of acidic liquid on the housing equipment (Chai et al., 2017). Therefore, improved litter handling methods need to be identified for reducing NH_3 generation while spraying neutral pH liquid agents (e.g., neutral EW, or NEW) to control PM and AB levels in CF houses.

Moore et al. (1995, 1996, 2000) found that a number of minerals (e.g., calcium hydroxide, aluminum sulfate, and ferrous sulfate) could be applied to reduce NH_3 emissions from poultry manure and litter. Terzich et al. (1998) identified that poultry litter treatment (PLT, a mixture of 93.2% sodium hydrogen sulfate and 6.5% sodium sulfate) could improve the health and body weight of broilers significantly ($p < 0.03$) by reducing indoor NH_3 levels. Liang et al. (2005a) tested the surface application of clinoptilolite zeolite onto layer manure at a rate of 0%, 2.5%, 5%, or 10% (0, 3.125, 6.25, or 12.5 kg m^{-2}, respectively), which reduced NH_3 emissions by 20%, 50%, and 77%, respectively, over a two-week storage period. Li et al. (2008) systematically tested litter treatment agents including zeolite, two forms of Al^+ Clear (48.5% liquid and granular aluminum sulfate, $Al_2{\cdot}(SO4)_3{\cdot}14H_2O$), Ferix-3 (ferric sulfate, $Fe_2(SO_4)_3{\cdot}9H_2O$), and PLT for NH_3 reduction and reported NH_3 reduction efficiencies of 33% to 94% for stored layer manure. Li et al. (2013) tested PLT for reducing NH_3 emissions during broiler brooding; the results showed that application rates of 183 and 366 g m^{-2} could reduce cumulative NH_3 emissions by 55% to 64.5%, with no significant difference in body weight or feed conversion of the birds as compared with the control. Fairchild et al. (2006) evaluated NH_3 reduction with increased application rates of sodium bisulfate (PLT) to determine the lifespan mitigation ability in commercial broiler houses and reported that NH_3 reduction was positively related to the amount of litter additive applied. Purswell et al. (2013) tested a sodium bisulfate-based litter amendment at a rate of 0.48 kg m^{-2}, which reduced NH_3 emissions by 56.6% on d42 (after three biweekly application) as compared to the control (no amendment application) in a tunnel-ventilated research facility housing 920 broiler chickens.

Most of the documented studies on the efficacy of litter additives focused on broiler or turkey houses, where the litter has considerably different physiochemical characteristics (e.g., depth, composition, moisture content, and pH) from CF hen houses. For example, litter in CF hen houses generally has much lower LMC than that in meat-bird houses (e.g., 10% to 15% for aviary litter vs. 25% to 35% for broiler or turkey litter) (Zhao et al., 2013), which could result in different litter pH when the same amount of litter additive is applied. Litter depth on a CF house floor varies considerably over time, depending on accumulation time or removal frequency of the litter and manure. In addition, litter in CF houses tends to contain a higher percentage of manure than that in meat-bird houses due to the different amounts of bedding used in the housing. Furthermore, there is no report on application of litter additive together with electrolyzed water to simultaneously control NH_3 and PM in CF houses.

The objectives of this study were to (1) assess the ammonia reduction efficiency of applying a commercial litter additive to CF hen house litter together with intermittent spray of neutral electrolyzed water (NEW) and (2) identify a suitable application rate of the litter additive for ammonia control that will be further evaluated in subsequent field verification tests.

Materials and Methods

Experimental Setup

The experiment was carried out with four identical dynamic emission chambers (DECs, each measuring 86 cm long, 46 cm wide, and 66 cm high; fig. 1) located in an environmentally controlled room. Litter was collected from a commercial CF farm in Iowa and stored in containers. One DEC served as the control (without litter additive), and the other three were used for treatments. The litter inside each DEC was tilled automatically with a rake driven by a stepper motor to mimic the activities of birds on the litter. The tilling time was 12:00 to 22:00 h, corresponding to the typical litter access period of birds in commercial CF houses. Air temperature and relative humidity (RH) in all DECs were controlled to simulate CF house conditions (22°C and 60% RH).

The granular litter additive PLT (sodium bisulfate, $NaHSO_4$) was chosen for this study because it is a cost-effective and safe (to animal) litter acidifier (Knueven, 1999; Li et al., 2013). When PLT is applied, it breaks down into sodium, hydrogen, and sulfate. The hydrogen ion lowers the pH and converts ammonia (NH_3) to ammonium (NH_4). The application rate of PLT recommended by the manufacturer is 0.37 to 0.74 kg m^{-2} (75 to 150 lb per 1000 ft^2) for broiler or turkey houses to control NH_3 levels for up to two weeks. In each DEC, 5 kg of litter (dry basis) was placed in a 50 L container (approx. 4.5 cm depth) and received topical application of

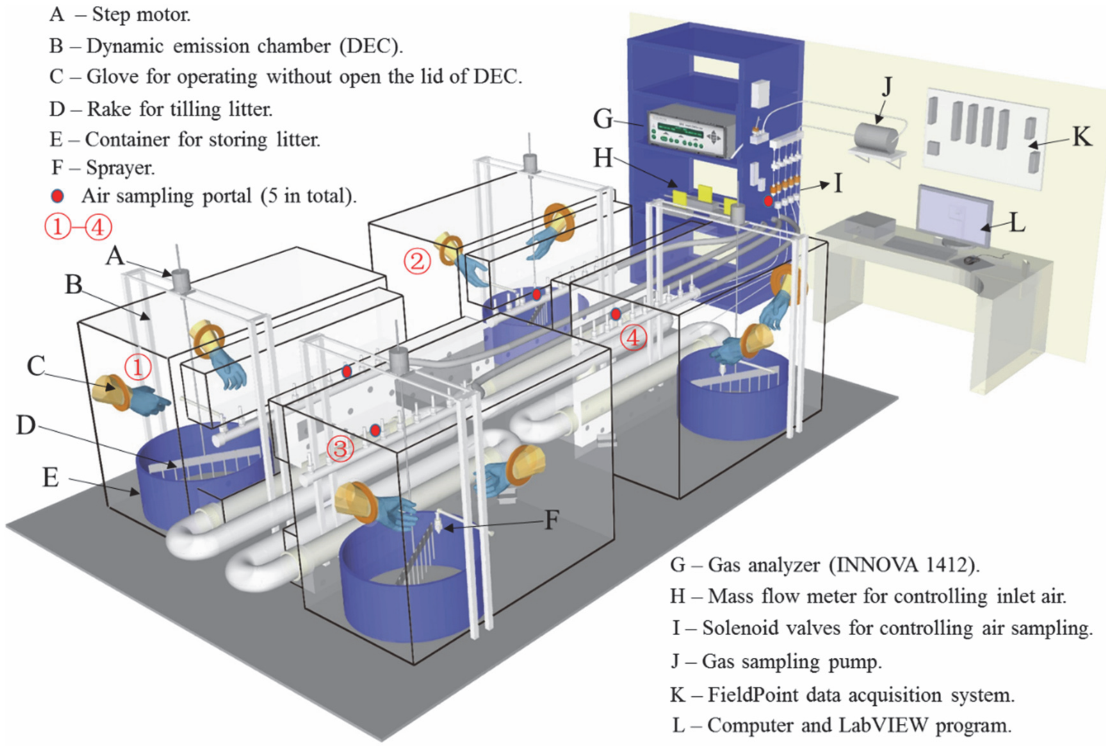

Figure 1. Experimental setup for NH_3 mitigation test with dynamic emission chambers.

PLT at a rate of 0.01, 0.02, or 0.03 kg kg^{-1} dry litter (i.e., 0.3, 0.6, and 0.9 kg m^{-2}). The three application rates were considered low, medium, and high levels, denoted Low-LA, Med-LA, and High-LA, respectively (fig. 2). In each trial, the three LA application rates were compared to the control (no LA) for 14 d, and four trials were conducted per regimen. The DECs were cleaned completely after each trial, and a minimum of 3 d downtime was used before running the next trial. Assignments of the control or treatments followed a Latin square design to avoid potential DEC effect (table 1).

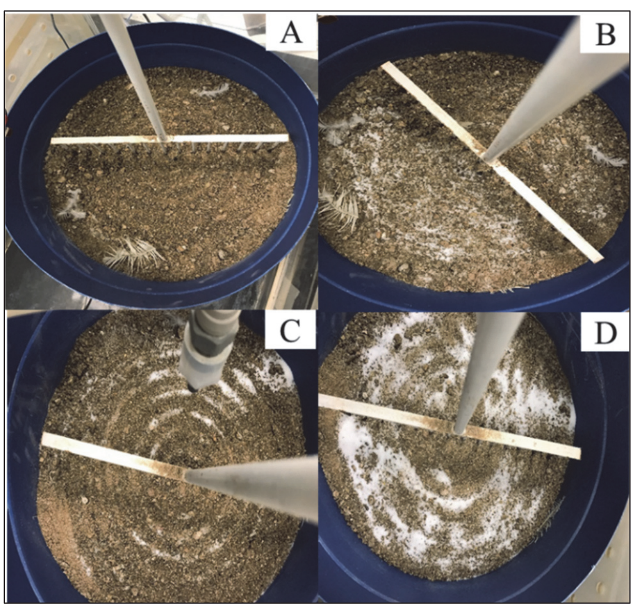

Figure 2. Topical application or absence of PLT on litter in control and treatment DECs: A = control (no LA), B = Low-LA, C = Med-LA, and D = High-LA with PLT application rates of 0, 0.01, 0.02, and 0.03 kg kg^{-1} dry litter, respectively.

Neutral electrolyzed water (NEW) at a dosage of 25 mL kg^{-1} dry litter was sprayed once a day on the litter in the control and treatment DECs between 11:30 and 12:00 h for 11 consecutive days and then stopped for three days (i.e., d12 to d14). This arrangement was intended to assess the changes in the NH_3 and PM levels after stopping the liquid spray for some time. In a previous study (Chai et al., 2017), the NEW spray dosage of 25 mL kg^{-1} dry litter was shown to result in relatively low increase in NH_3 emissions and 60% to 70% reduction in PM.

Litter Handling and NEW Preparation

Litter collected from a commercial aviary CF farm in central Iowa was transported to our laboratory in polyethylene plastic bags to prevent nutrient or moisture loss, and then stored at -20°C to preserve the nutrients and moisture before experiment use. For each trial, about 20 kg (dry basis, 5 kg dry litter for each DEC) was transferred to a cold room (4°C), thawed for two days, and then stored at room temperature for one day before experiment use. The thawed litter was completely mixed, equally divided, and randomly as-

Table 1. Assignment of treatment and control regimens among the four dynamic emission chambers (DECs).[a]

DEC	Experimental Regimen of the Trial 1	2	3	4
1	Control	High-LA	Med-LA	Low-LA
2	Low-LA	Control	High-LA	Med-LA
3	Med-LA	Low-LA	Control	High-LA
4	High-LA	Med-LA	Low-LA	Control

[a] Control, Low-LA, Med-LA, and High-LA represent no litter additive (LA) and low, medium, and high LA application rates of 0.01, 0.02, and 0.03 kg kg^{-1} dry litter, respectively. The same dosage (25 mL kg^{-1} dry litter) of neutral electrolyzed water (NEW) was sprayed in each DEC once a day.

signed to the four DECs for testing. The LMC at the start and during each of the experimental days was measured by oven-drying approximately 10 g litter samples at 105°C for 24 h. The litter pH was determined with a pH meter (XL15, Fisher Scientific, Hampton, N.H.) after mixing the litter sample with deionized water (10% solution; 2 g litter and 20 mL water). The litter samples used for LMC and pH measurements were collected from four surface locations of the litter in each DEC. Air sampling for each DEC was 12 min in each cycle (1 h), so there was a 48 min interval when the air was not sampled. The litter samples were collected during this interval with the attached gloves (fig. 1) to reduce disturbance of the air sampling. In addition, the lid of each DEC was partially opened for only a short time (<5 s) for removing the litter sample. Therefore, the potential effect of litter sampling on the measured NH_3 concentration was low and could be neglected.

The NEW was produced using an electrolyzing container with 0.1% NaCl solution (Zhao et al., 2014). Free chlorine (FC) was produced at a rate of 4.9 mg L^{-1} min^{-1} at 8 VDC, and an FC concentration of 200 mg L^{-1} was generated and used in the current study. The newly generated NEW was stored in a cold room (4°C) before each spray, during which time its pH value was measured once every two days.

MONITORING OF AMMONIA AND PM LEVELS

Concentrations of NH_3 in the exhaust air of each DEC were measured continually with a photoacoustic multi-gas analyzer (model 1412, Innova AirTech Instruments, Ballerup, Denmark). Because one gas analyzer was used to measure all four DECs, the air samples from all locations were taken sequentially using an automatically controlled gas sampling system (fig. 1). Considering the relatively stable nature of the gaseous concentrations in the DECs, the air in each DEC was sampled for 12 min, with the first 10 min for stabilization and the last 2 min for measurement. This sequential measurement yielded hourly data of NH_3 concentrations for the four DECs' exhaust air and one inlet air. The Innova analyzer was checked weekly with standard zero and span gases. The ammonia emission rate (ER) of each DEC was determined from the ventilation rate and the concentration difference between the exhaust air and inlet air of each DEC using the following equation (Liang et al., 2005b; Chai et al., 2017):

$$\begin{aligned} ER_{NH_3 i} &= \frac{1}{M} \times Q_i \times \left(C_{NH_3,ex} - C_{NH_3,in}\right) \\ &\times 10^{-6} \times \frac{W_{NH_3}}{V_{m,NH_3}} \times \frac{T_{sd}}{T_i} \times \frac{P_a}{P_{sd}} \end{aligned} \quad (1)$$

where

$ER_{NH_3 i}$ = NH_3 emission rate of DEC i (i = 1, 2, 3, 4) (g kg^{-1} dry litter d^{-1})

M = amount of litter (dry weight) in each DEC (kg)

$C_{NH_3,in}$ and $C_{NH_3,ex}$ = NH_3 concentrations of inlet and exhaust air (ppm)

Q_i = ventilation rate of DEC i

W_{NH_3} = molar weight of NH_3 gas (17.031 g $mole^{-1}$)

V_{m,NH_3} = molar volume of NH_3 at standard temperature (°C) and pressure (101.325 kPa) (0.022414 m^3 $mole^{-1}$)

T_{sd} = standard temperature (273.15 K)

T_{ai} = absolute temperature in DECs (K)

P_{sd} = standard barometric pressure (101.325 kPa)

P_a = atmospheric barometric pressure at the site (98 kPa).

An optical PM sensor (DustTrak DRX Aerosol Monitor 8533, TSI Inc., Shoreview, Minn.) was used to measure PM concentrations of different particle sizes, i.e., PM_1, $PM_{2.5}$, PM_4, PM_{10}, and total suspended particulate (TSP), simultaneously in the DECs after spraying NEW to assess the PM reduction efficiency. The measurable range of the DustTrak 8533 was 0.001 to 150 mg m^{-3} for PM concentration. In addition to air quality, the air temperature, RH, and ventilation rate of the DECs were monitored with a LabVIEW program and associated I/O hardware (fig. 1) (National Instruments, Austin, Tex.). The LabVIEW program was also used to control the operation of the mixing-rake motor and the gas sampling solenoid valves.

Statistical analyses were performed using R software version 3.3.3 (R Core Team, 2014). Tukey's honestly significant difference (HSD) was applied in conjunction with ANOVA (post-hoc analysis) to test for effects of litter additive on NH_3 emissions. In conducting the ANOVA, the null hypothesis was that there was no difference in means of NH_3 emissions among treatments and control; when the null hypothesis was rejected, we considered means of treatments and control significantly different from each other. Equation 2 is the statistical model for the data analysis:

$$Y_i = \mu + L_i + e_i \quad (2)$$

where

Y_i = independent observation (NH_3 concentrations or ER) for litter additive rate i

μ = overall mean

L_i = litter additive application effect (fixed)

e_i = random error with $N \sim (0, \sigma^2)$.

In addition, t-tests were performed to evaluate the differences in air temperature, RH, LMC, and pH among DECs over days. Differences were considered significant at $p < 0.05$.

RESULTS AND DISCUSSION

THERMAL ENVIRONMENT

The air temperature and RH in the control and treatment DECs during 14 d of measurement are shown in figure 3. As indicated by the data, the air temperature and RH in all DECs were generally close to the set points of 22°C and 60%. The ventilation rate in all DECs was maintained close to the target value of 6 L min^{-1} (mean ±SD = 6.0 to 6.09 ±0.2; n = 14).

LITTER MOISTURE CONTENT AND PH

LMC and pH are two primary factors affecting NH_3 emissions and reduction. The variations in LMC during each trial are shown in table 2. LMC in all four DECs was similar as a result of the once-a-day NEW application. LMC increased from 10.3% ±0.1% on d1 before spray to 16.1% ±0.3% on d10 after nine consecutive once-a-day sprays, i.e., about a 60% increase. LMC on d13 was lower than on d10 as the NEW spray had been stopped since d12. After stopping the NEW spray, evaporation of litter moisture and litter tilling

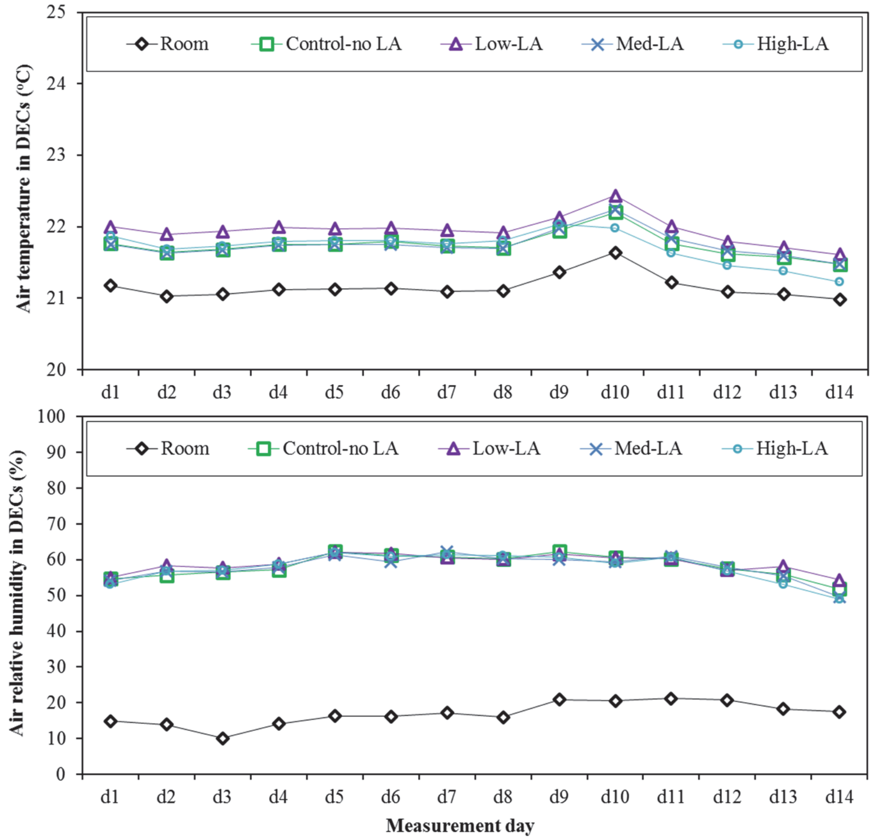

Figure 3. Air temperature and RH in DECs over the 14-d measurement period.

Table 2. Averaged litter moisture content (%) of the four DECs on five days (mean ±SD, *n* = 4).[a]

Day	Trial 1	Trial 2	Trial 3	Trial 4	Mean ±SD
d1	10.1 ±0.1 e	10.3 ±0.1 e	10.4 ±0.2 e	10.3 ±0.3 d	10.3 ±0.1 e
d4	13.5 ±0.3 d	13.8 ±0.2 d	14.2 ±0.2 d	14.0 ±0.2 c	13.9 ±0.3 d
d7	14.9 ±0.3 b	15.2 ±0.2 b	15.5 ±0.2 b	15.1 ±0.2 b	15.2 ±0.3 b
d10	15.8 ±0.2 a	16.2 ±0.1 a	16.5 ±0.2 a	16.1 ±0.2 a	16.1 ±0.3 a
d13	14.3 ±0.2 c	14.7 ±0.4 c	14.9 ±0.3 c	14.8 ±0.2 b	14.7 ±0.3 c

[a] Days d1 through d13 are days when litter was sampled for drying at 10:00 h. Means in the same row followed by different letters are significantly different at $p \leq 0.05$. The neutral electrolyzed water (NEW) spray dosage was 25 mL kg^{-1} dry litter d^{-1}.

both accelerated the loss of moisture from litter to air.

Litter pH in all regimens corresponded well to the PLT application rate. Higher PLT application resulted in significantly lower litter pH ($p < 0.05$) (table 3). The control regimen had a relatively stable pH of 7.1 to 7.3 over the two-week period. For the Low-LA, Med-LA, and High-LA regimens, litter pH was 5.7, 3.6, and 3.1, respectively, on d1 immediately after PLT application. The applied PLT broke down into sodium, hydrogen, and sulfate, and the hydrogen ions lowered the pH. After two weeks, the litter pH of the treatment DECs increased to 6.9, 5.8, and 5.2, respectively, which arose from the continuous reaction of the finite and less available amount of PLT with the mixed litter. In addition, spraying the NEW (pH of 7.9) onto the litter might have contributed somewhat to the elevated litter pH.

Table 3. Litter pH in treatment and control DEC (mean ±SD, *n* = 4).[a]

Day	Control (no LA)	Low-LA	Med-LA	High-LA	Deionized Water
d1	7.1 ±0.1 a	5.7 ±0.2 b	3.6 ±0.2 c	3.1 ±0.3 d	8.3 ±0.1
d3	7.1 ±0.0 a	6.0 ±0.1 b	4.8 ±0.2 c	3.9 ±0.2 d	8.2 ±0.0
d5	7.1 ±0.1 a	6.1 ±0.1 b	5.1 ±0.2 c	4.1 ±0.2 d	8.2 ±0.0
d7	7.2 ±0.1 a	6.3 ±0.1 b	5.4 ±0.2 c	4.6 ±0.2 d	8.2 ±0.0
d9	7.2 ±0.1 a	6.5 ±0.1 b	5.6 ±0.3 c	5.0 ±0.2 d	8.2 ±0.0
d11	7.3 ±0.1 a	6.7 ±0.2 b	5.7 ±0.3 c	5.1 ±0.2 d	8.2 ±0.1
d13	7.2 ±0.1 a	6.9 ±0.1 ab	5.8 ±0.3 c	5.2 ±0.2 d	8.2 ±0.1
Mean ±SD	7.2 ±0.1	6.3 ±0.4	5.1 ±0.8	4.4 ±0.8	8.2 ±0.0

[a] Low-LA, Med-LA, and High-LA represent low, medium, and high application rates of litter additive (i.e., 0.01, 0.02, and 0.03 kg kg^{-1} dry litter, or 0.3, 0.6, and 0.9 kg m^{-2}, respectively). Days d1 through d13 are days when litter was sampled at 10:00 h for pH measurement. Means in the same row followed by different letters are significantly different at $p \leq 0.05$. Neutral electrolyzed water (NEW) with pH 7.9 ±0.1 was sprayed at a dosage of 25 mL kg^{-1} dry litter d^{-1} once a day, and litter additive (i.e., PLT) was tested with pH of 0.7.

Ammonia and PM Reduction Efficiency

Daily NH_3 emissions of the control and treatment regimens over the 14 d test period are shown in figure 4. The control regimen showed a faster increase in NH_3 ER than the treatments. Except for High-LA, all regimens showed gradually increasing NH_3 ER until d12, when the NEW spray stopped. Increased emissions of NH_3 were caused by the LMC, which increased by 60% with the once-a-day NEW spray. Similar results for NH_3 elevation were reported by Ogink et al. (2012) after spraying regular tap water on CF hen house litter.

After the NEW spray stopped, NH_3 ER started to decline on d12 due to reduced LMC. On d14, NH_3 emissions in the Med-LA and High-LA regimens remained at relatively low levels, which implies that the mitigation effect of PLT at

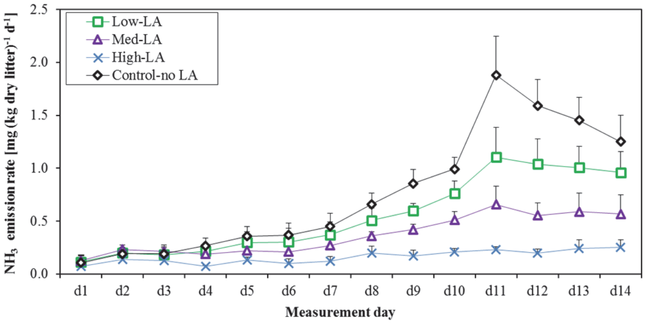

Figure 4. Daily NH_3 emission rates from treatment and control DECs (mean ±SE, n = 4). Control-no LA represents no LA application, and Low-LA, Med-LA, and High-LA represent low, medium, and high application rates of litter additive, i.e., 0.3, 0.6, and 0.9 kg m^{-2}, respectively.

higher application rates may last longer than two weeks for CF hen litter. To quantify the mitigation effect of PLT over a longer period after application, the measurement period will be extended (e.g., four weeks) in a subsequent field verification study.

The cumulative emissions of NH_3 in the control and treatment regimens were 53.1 ±4.4, 38.3 ±5.2, 25.6 ±3.0, and 11.3 ±1.4 g (mean ±SE), respectively, from 5 kg dry basis litter over the 14 d period (fig. 5). Daily mean NH_3 ER of the control, Low-LA, Med-LA, and High-LA regimens were 0.76 ±0.05, 0.55 ±0.06, 0.37 ±0.04, and 0.16 ±0.02 g kg^{-1} dry litter d^{-1} (mean ±SE), respectively. Treatment DECs showed significantly lower NH_3 emissions than the control ($p < 0.05$). A higher LA application rate resulted in lower NH_3 emissions. The NH_3 reduction efficiency of the Med-LA regimen averaged 33% lower than that of the Low-LA regimen, trending significantly different ($p = 0.075$).

The current study showed that NH_3 reduction efficiency is directly proportional to PLT application rate ($p < 0.05$). This outcome agrees with the findings reported by Fairchild et al. (2006) for commercial broiler houses. As shown in figure 6, the reduction efficiencies for the Low-LA (0.01 kg kg^{-1} dry litter), Med-LA (0.02 kg kg^{-1} dry litter), and High-LA (0.03 kg kg^{-1} dry litter) regimens were 28%, 52%, and 79%, respectively, relative to the control (no LA). The following linear equation depicts the relationship well:

$$NH_3 \text{ reduction efficiency (\%)} = 262.9\ (\pm 10.8) \times (\text{PLT rate, kg kg}^{-1} \text{ dry litter}) \quad (3)$$

$$(R^2 = 0.9978)$$

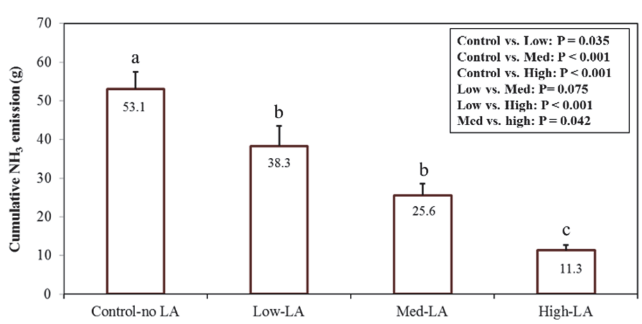

Figure 5. Cumulative NH_3 emissions of the treatments and control during 14 d test (mean ±SE). Control-no LA, Low-LA, Med-LA, and High-LA represent litter additive application rates of 0, 0.3, 0.6, and 0.9 kg m^{-2}, respectively. Different letters above the data bars represent significant difference at $p < 0.05$.

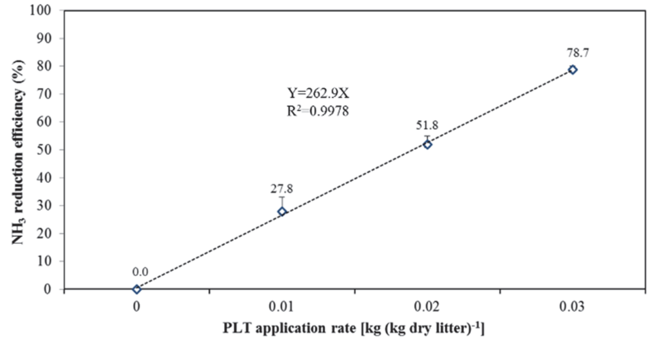

Figure 6. Ammonia (NH_3) reduction efficiency versus PLT application.

The NH_3 reduction efficiencies with PLT application observed in the current study (i.e., 28% to 79%) were lower than the results of 74% to 92% reported by Li et al. (2008). The difference is speculated to stem from the higher PLT application rates (0.5 to 1.5 kg m^{-2}) in the comparison study. In addition, the litter in the current study was tilled to mimic birds' activities on the floor of CF hen houses, whereas the litter was stored under static conditions without disturbance in the comparison study. Tilling the litter to mimic birds' behavior of dust bathing and foraging is expected to accelerate NH_3 emissions, as the exchange between the air and litter is enhanced.

In commercial CF houses, floor litter depth varies with time depending on flock age, litter removal frequency, and bird management (e.g., daily length of litter access period). A large range of litter depths (0.7 to 5.4 cm) was reported by Campbell et al. (2016). Thus, the application rate of the litter additive should be adjusted based on the actual litter depth on the floor. The litter depth in the current laboratory test was 4.5 cm, and the PLT application rates of low, medium, and high were equivalent to 0.067, 0.133, and 0.2 kg m^{-2} per cm litter depth, or 13.6, 27.3, and 40.9 lb per 1000 ft^2 per cm (0.4 in.) litter depth.

The $PM_{2.5}$, PM_{10}, and TSP levels were reduced from 3.83, 6.39, and 7 mg m^{-3} to 0.07, 0.14, and 0.15 mg m^{-3}, respectively, after 11 once-a-day NEW sprays due to the increase in LMC (fig. 7 and table 4). The PM reduction efficiency after the first spray was about 70%, which agreed with the results reported in an earlier study in our laboratory (Chai et al., 2017). After the NEW spray stopped, the PM concentrations started to rise due to the loss of moisture from the litter,

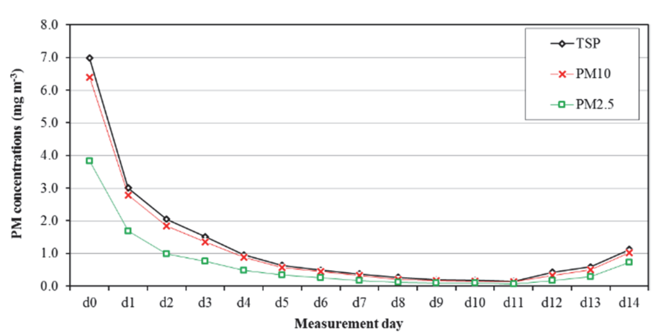

Figure 7. Daily mean concentrations of $PM_{2.5}$, PM_{10}, and TSP in treatment and control DECs.

Table 4. Temporal concentrations (mg m^{-3}) of different-size PM under once-a-day NEW spray at 25 mL kg^{-1} dry litter (mean ±SD, *n* = 4).

Day[a]	PM_1	$PM_{2.5}$	PM_4	PM_{10}	TSP
Before spray	3.55 ±0.63	3.83 ±0.66	4.47 ±0.66	6.39 ±0.55	7.00 ±0.46
d1	1.53 ±0.24	1.68 ±0.30	1.98 ±0.31	2.78 ±0.41	3.01 ±0.44
d2	0.89 ±0.07	1.68 ±0.10	1.98 ±0.12	2.78 ±0.18	3.01 ±0.13
d3	0.69 ±0.12	0.76 ±0.14	0.90 ±0.18	1.35 ±0.24	1.52 ±0.23
d4	0.44 ±0.06	0.48 ±0.06	0.59 ±0.07	0.88 ±0.15	0.96 ±0.17
d5	0.32 ±0.03	0.35 ±0.03	0.41 ±0.04	0.57 ±0.05	0.63 ±0.03
d6	0.22 ±0.01	0.25 ±0.01	0.30 ±0.01	0.44 ±0.03	0.48 ±0.04
d7	0.15 ±0.01	0.16 ±0.01	0.20 ±0.01	0.33 ±0.01	0.38 ±0.02
d8	0.12 ±0.00	0.12 ±0.01	0.13 ±0.02	0.20 ±0.01	0.27 ±0.01
d9	0.08 ±0.04	0.09 ±0.04	0.11 ±0.04	0.17 ±0.02	0.19 ±0.02
d10	0.09 ±0.01	0.10 ±0.01	0.11 ±0.01	0.15 ±0.02	0.17 ±0.03
d11	0.06 ±0.01	0.07 ±0.01	0.09 ±0.01	0.14 ±0.01	0.15 ±0.01
d12	0.16 ±0.01	0.17 ±0.01	0.20 ±0.02	0.33 ±0.02	0.39 ±0.02
d13	0.26 ±0.15	0.29 ±0.14	0.33 ±0.13	0.50 ±0.08	0.59 ±0.08
d14	0.66 ±0.07	0.72 ±0.07	0.80 ±0.06	1.02 ±0.02	1.12 ±0.07

[a] PM concentration was monitored from 17:00 to 18:00 h (midway of litter tilling period of 12:00 to 22:00 h) from d1 to d14 after NEW spray.

as shown in table 2. On d14, three days after stopping the NEW spray, the $PM_{2.5}$, PM_{10}, and TSP levels rebounded to 0.72, 1.02, and 1.12 mg m^{-3}. The PM reduction efficiency, together with the NH_3 reduction efficiency, will be verified in a subsequent field study in a commercial aviary CF hen house. Further information about reduction for different sizes of PM can be found in table 4.

Field verification of these lab-scale findings is underway at a commercial CF farm in central Iowa where the litter samples used in the current study were collected. In addition to verifying the mitigation efficiency of NH_3 and PM, the economic performance of applying litter additives to reduce NH_3 emissions and increase the nitrogen content of the manure will be assessed. The litter additive (PLT) tested in the current study costs about \$800 per metric ton, based on a price quote from a local vendor (Best Vet Solutions, Ellsworth Iowa) in March 2017. The operational cost (PLT cost and labor cost) for a commercial CF house (50,000 laying hens with litter floor area of 2400 m^2) is estimated to be \$0.122, \$0.239, and \$0.356 bird^{-1} year^{-1} at PLT application rates of 0.3, 0.6, and 0.9 kg m^{-2} (or 60.8, 121.6, and 184.2 lb per 1000 ft^2), respectively, and an application frequency of once a month. A trade-off between NH_3 reduction and litter additive application will be evaluated for the commercial CF egg production.

Summary and Conclusions

A lab-scale study was conducted to assess the efficacy of PLT, a commercial poultry litter additive (LA), at three application rates (low, medium, and high) relative to a control (no application) in reducing ammonia (NH_3) emissions from cage-free (CF) hen house litter together with sprays of neutral electrolyzed water (NEW) for PM control. The following observations and conclusions were made:

- Ammonia emission rates for the control (no LA), Low-LA, Med-LA, and High-LA regimens averaged 0.76, 0.55, 0.37, and 0.16 g kg^{-1} dry litter d^{-1}, respectively, yielding 28% to 79% reduction in NH_3 emission by the treatments. The NH_3 reduction efficiency was linearly proportional to the PLT application rate, with higher application rate resulting in significantly lower litter pH ($p < 0.05$).
- The $PM_{2.5}$, PM_{10}, and TSP levels were reduced from 3.83, 6.39, and 7.00 mg m^{-3} before the NEW spray to 0.07, 0.14, and 0.15 mg m^{-3} after 11 once-a-day NEW sprays. Following a 3 d suspension of the NEW spray, the PM levels rebounded to 0.72, 1.02, and 1.12 mg m^{-3} for $PM_{2.5}$, PM_{10}, and TSP, respectively, due to reduced litter moisture content.
- While higher LA application rates further suppressed NH_3 emissions, a balance between NH_3 reduction and the cost associated with the additive application needs to be considered for commercial CF production. This economic balance will be evaluated in a future field verification test, based on these lab-scale findings.

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